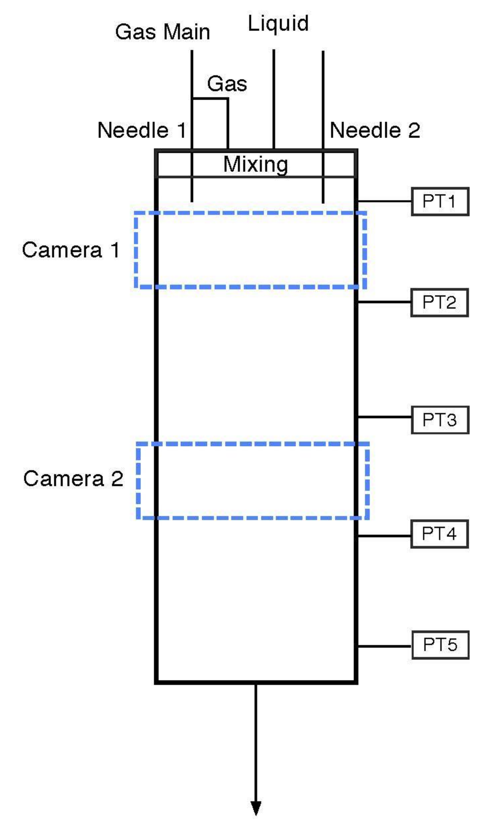
Gas-Liquid Two-Phase Flow in Permeable Media in the Absence of Gravity

Mahsa Taghavi[1], Brian Motil[2], Vemuri Balakotaiah[1]

[1]Chemical and Biomolecular Engineering Department, University of Houston, Houston, TX | [2]NASA Glenn Research Center, Cleveland, OH

Motivation

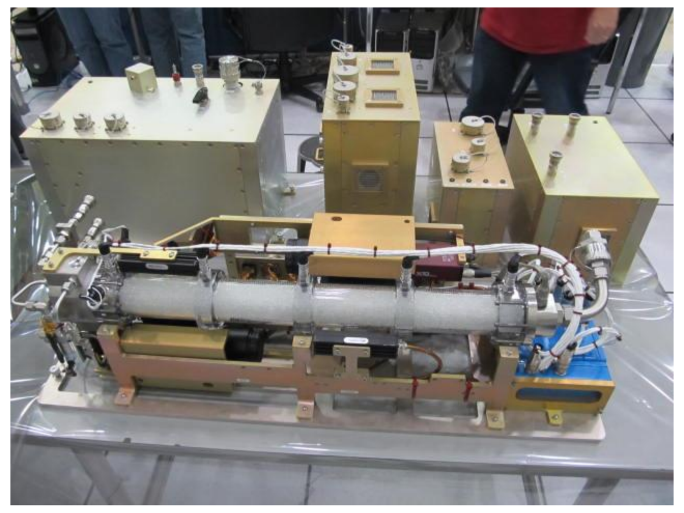


- Packed Bed Reactors (PBRs) are widely used in industry to carry out many reaction and separation processes.
- Due to its compact size, versatility, reliability, and low operational power, a packed bed is a viable unit operation in support of various stages of water treatment in long-duration human space travels and deep-space missions.
- While design rules for gas-liquid flows through packed beds in normal gravity have been known for decades, they are lacking for microgravity environments, where capillary effects dominate.

Objectives

- The Packed Bed Reactor Experiment (PBRE) focuses exclusively on the hydrodynamics of these flows, specifically on flow regime map, holdup, and pressure drop correlations.
- The main goal is to develop a simple method to estimate pressure drop through porous media in the microgravity environment.

Experimental



- **PBRE** Setup: A cylindrical reactor of 60 cm in length and 5 cm in diameter having two identical test columns to examine the effect of packing wettability:
  - First test section: 3 mm spherical glass beads (wetting material).
  - Second test section: 3 mm Teflon beads (non-wetting material).
- **PBRE-2** Setup: Several modifications to improve the flow loop for enabling accurate pressure readings:
  - Test section: 2 mm glass beads.

Friction Factor and Pressure Drop

Ergun equation for single-phase flow: $f_{SP} = \frac{C_V}{Re^*_{LS}} + C_I$

Two-phase friction factor: $f_{TP} = f_{SP} + C_S\left(Re^*_{GS}\right)^{\alpha}\left(Re^*_{LS}\right)^{\beta} Su_L^{\gamma}$

$$f_{TP} = f_{SP} + \underbrace{C_S\left(Re^*_{GS}\right)^{\alpha}\left(Ca^*_{LS}\right)^{\beta} Su_L^{\beta+\gamma}}_{\text{Dynamic phase interaction term}}$$

$$f_{TP} \equiv \frac{-\Delta P}{Z}\,\frac{d_p}{\rho_L U_{LS}^2}\,\frac{\varepsilon^3}{1-\varepsilon}$$

$$Su_L = \frac{d_p \rho_L \sigma}{\mu_L^2}$$

$$Ca^*_{LS} = \frac{\mu_L U_{LS}}{\sigma(1-\varepsilon)}$$

$$Re^*_{LS} = \frac{\rho_L U_{LS} d_p}{\mu_L(1-\varepsilon)}$$

Pressure gradient:

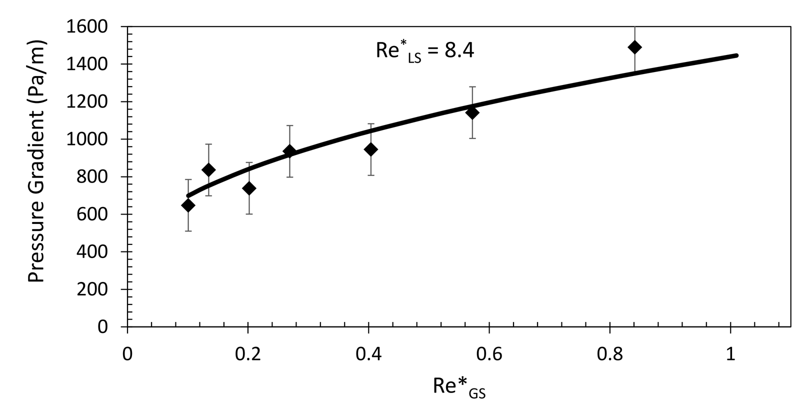
$$\frac{-\Delta P}{Z} = \underbrace{C_V \frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu_L U_{LS}}{d_p^2}}_{\text{Viscous}} + \underbrace{C_I \frac{(1-\varepsilon)}{\varepsilon^3}\frac{\rho_L U_{LS}^2}{d_p}}_{\text{Inertial}} + \underbrace{C_S \frac{(1-\varepsilon)}{\varepsilon^3}\left(\frac{\rho_l U_{LS}^2}{d_p}\right)\left(\frac{\rho_g U_{GS} d_p}{\mu_g(1-\varepsilon)}\right)^{\alpha}\left(\frac{\rho_l U_{LS} d_p}{\mu_l(1-\varepsilon)}\right)^{\beta}\left(\frac{d_p \rho_l \sigma}{\mu_l^2}\right)^{\gamma}}_{\text{Capillary}}$$

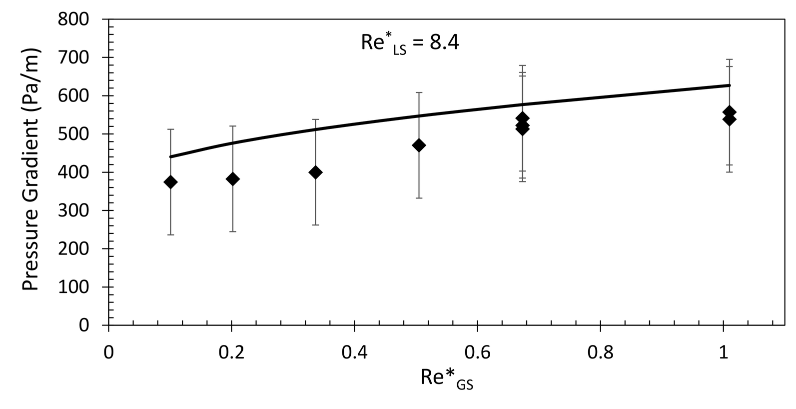
PBRE: Pressure Drop

For viscous-capillary (V-C) regime ($0.1 < Re^*_{GS} < 1$ and $1 < Re^*_{LS} < 10$):

Glass (wetting):
- Capillary term ~ 75%
- Viscous term ~ 23%

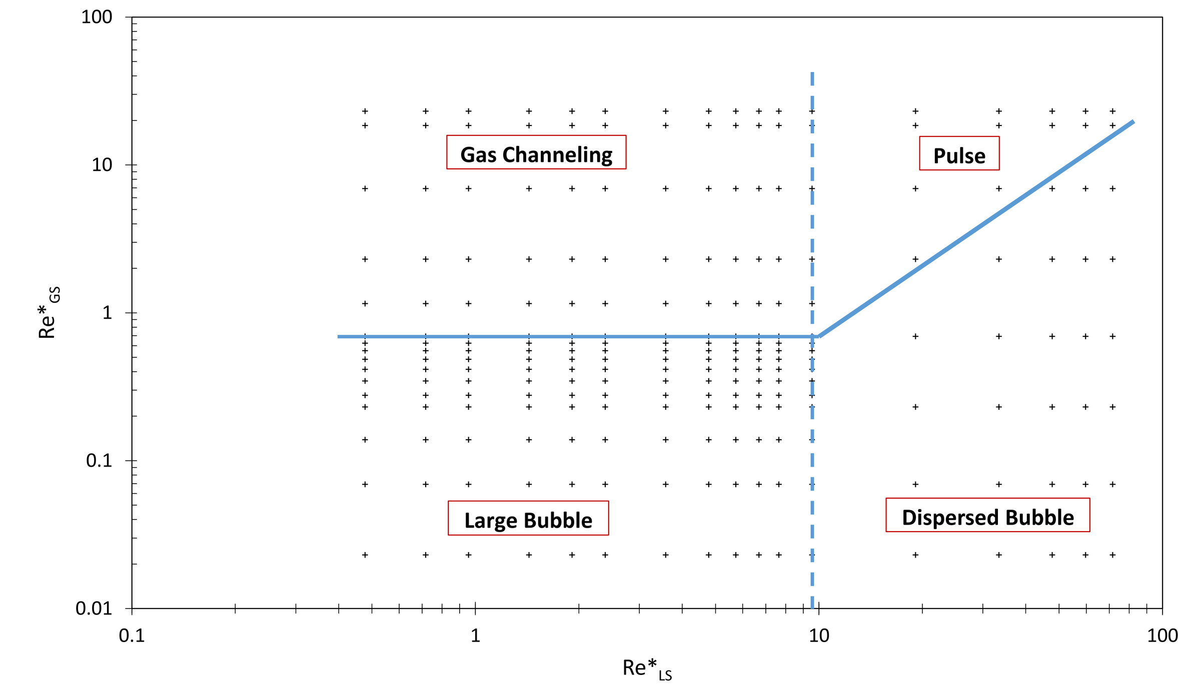
Teflon (non-wetting):
- Capillary term ~ 20-30%
- Viscous term ~ 70%





- In the V-C regime, the **capillary** (or phase interaction) contribution dominates the pressure drop for the wetting case versus the **viscous** contribution dominating in the non-wetting case.

PBRE-2: Flow Regime Map/ Friction Factor



Friction factor correlations:

Gas Channeling Regime

$$f_{TP} - f_{SP} = 0.19\left(Re^*_{GS}\right)^{0.69}\left(Re^*_{LS}\right)^{-1.85} Su_L^{2/3}$$

Dispersed Bubble Regime

$$f_{TP} - f_{SP} = 0.42\left(Re^*_{GS}\right)^{0.19}\left(Re^*_{LS}\right)^{-1.07} Su_L^{2/3}$$

Pulse Regime

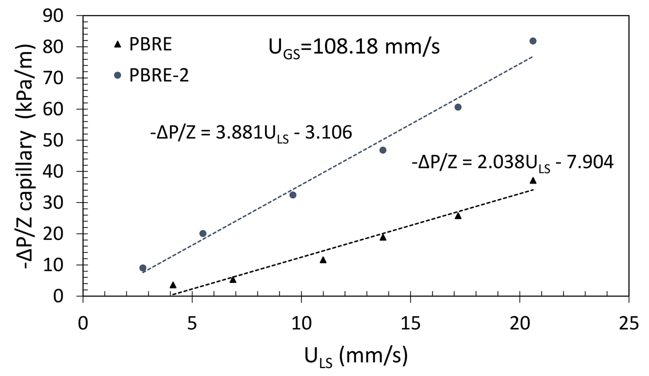
$$f_{TP} - f_{SP} = 1.02\left(Re^*_{GS}\right)^{0.44}\left(Re^*_{LS}\right)^{-1.61} Su_L^{2/3}$$

Flow regime map obtained by:
- Video observations
- Pressure gradient versus Re slope change
- Amplitude of pressure fluctuation (power spectrum)

$$Re^*_{GS} = 0,\ f_{SP} = \frac{C_V}{Re^*_{LS}} + C_I$$

$$C_V = 150.8,\ C_I = 1.78$$

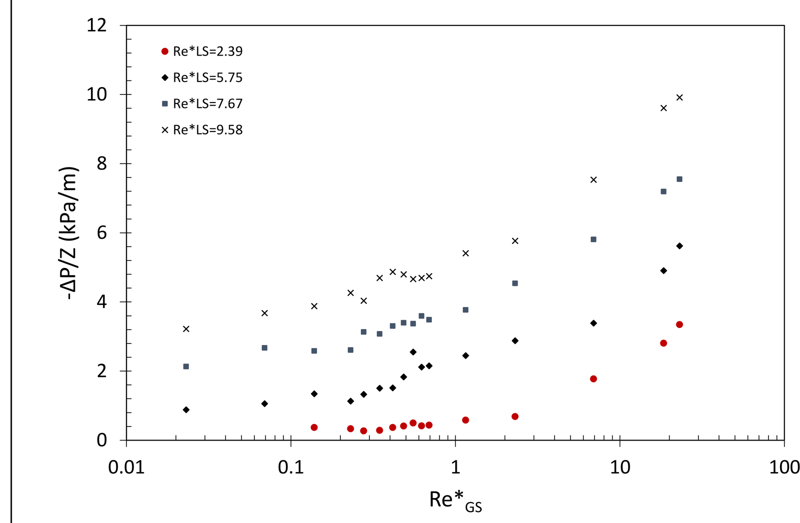
Effect of Particle Size

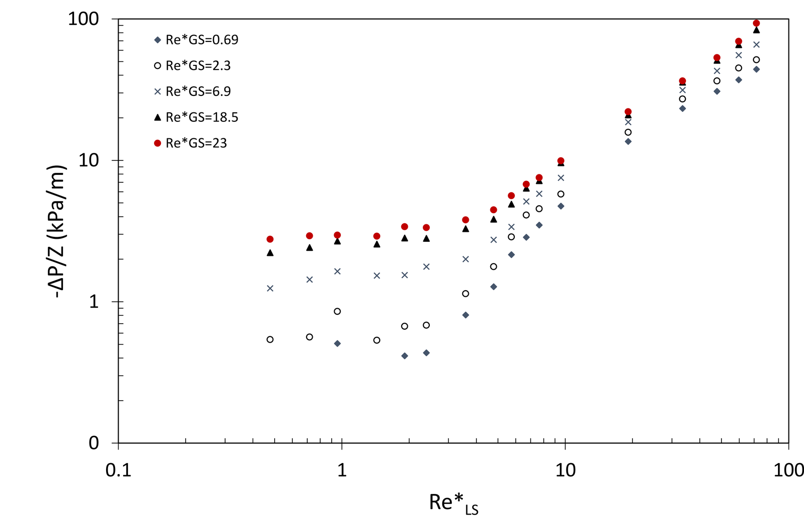


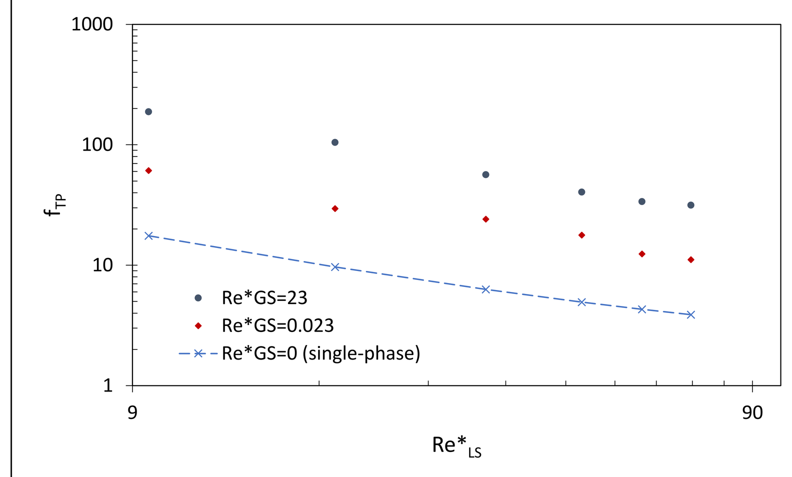
$$\left(-\Delta P/Z\right)_{2mm} \Big/ \left(-\Delta P/Z\right)_{3mm} \approx \left(d_{p,3mm}/d_{p,2mm}\right)^{1.133} \approx 1.58$$

- The capillary contribution is almost 1.5- 2 times higher for the 2mm PBRE-2 particles than the 3mm PBRE particles.
- Pressure gradient is proportional to the liquid superficial velocity and depends to a lesser extent on the gas superficial velocity.

Slope Change and Flow Regime Transition

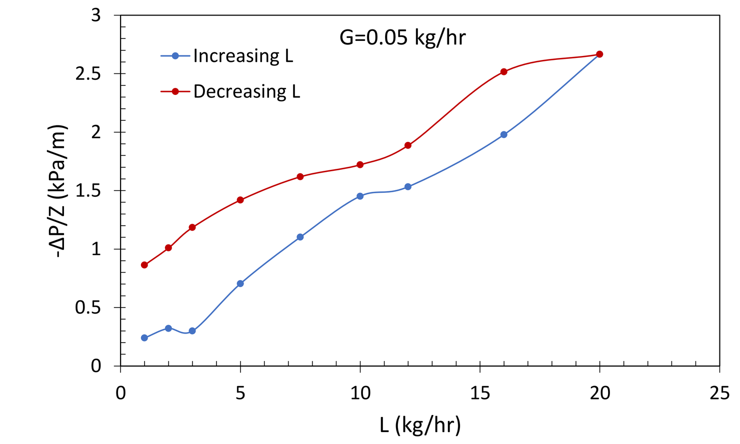




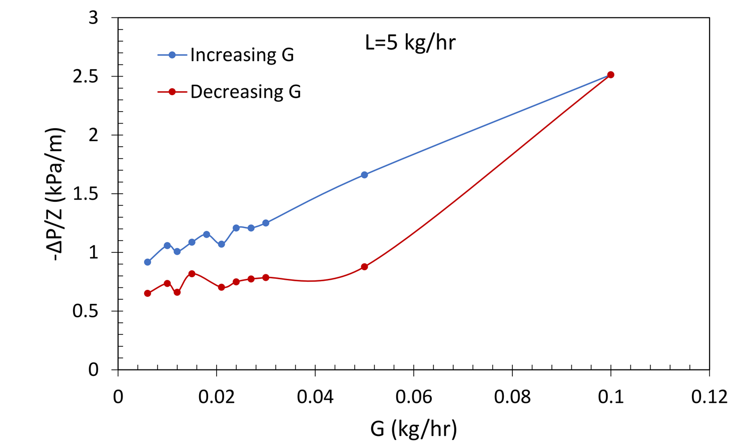


- Pressure gradient increases with increasing liquid Reynolds number for all gas flow rates.
- Two different slopes are observed in the figures. The slope change occurs at the flow regime transition points.

Hysteresis Effect in Microgravity



Hysteresis at constant gas flow rate



Hysteresis at constant liquid flow rate

- Increasing and then decreasing the liquid (gas) flow rate, at a fixed gas (liquid) flow leads to different values for the liquid holdup and pressure gradient within the V-C regime.
- Gas hold-up is a function of bed history at low liquid and gas flow rates.

Summary

- The pressure drop data from ISS PBRE microgravity experiments were analyzed in terms of a modified two-phase friction factor which encompasses contribution from viscous, inertial, and capillary forces.
- The capillary contribution to the pressure drop was found to be a strong function of the Capillary number. It was the dominant contribution even at the highest gas and liquid flow rates studied.
- Four flow regimes of large bubble, gas channeling, dispersed bubble, and pulse regimes were identified, and different friction factor correlations were developed for each regime.
- Hysteresis effect was observed within the V-C regime under microgravity.

References

- Taghavi, M., Motil, BJ., Nahra, H., Balakotaiah, V., Gas-liquid flows through porous media in microgravity: The Packed Bed Reactor Experiment-2, AIChE J, e17727 (2022).
- Motil, BJ., Rame, E., Salgi, P., Taghavi, M., Balakotaiah, V., Gas-liquid flows through porous media in microgravity: The International Space Station Packed Bed Reactor Experiment, AIChE J (2020).